Efficient Trade Space Exploration

Alfred Nash
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Alfred.E.Nash@JPL.NASA.Gov

Abstract — **Two of the principal challenges in efficient trade space exploration are (1) quickly evaluating options, and (2) quickly convincing stakeholders to accept the results of the evaluation. This paper describes the process and tools that have led to a factor of nine improvement in the efficiency of trade space exploration of space systems in Team-X at the Jet Propulsion Laboratory.**

The principal method that has enabled this increase in efficiency is the separation of the exploration figures of merit into two distinct types, which are then addressed in an efficient order. The figures of merit in a trade space exploration of N subsystems either scale with the number of interactions between subsystems, O(N^2-N), or with the number of interactions between the subsystems and the external constraints, O(N).

It is more computationally efficient to filter against O(N) figures of merit first, and only proceed to filtering against O(N^2-N) figures of merit if warranted, than the other way around. However, the latter is the typical bottoms up design approach in space systems engineering organizations.

In addition to the computational efficiencies gained through this pre-filtering of infeasible or non-viable configurations from further work, cognitive efficiencies are also gained by this partitioning of the figures of merit. By partitioning the O(N) external constraints on the system along the border of an N-squared diagram-based dashboard, and the O(N^2-N) of interfaces between subsystems within the dashboard, stakeholders gain several insights: (1) how the external boundary conditions inform the what the optimal internal subsystem choices are, (2) how the internal subsystem choices affect the selectability of the options, and perhaps most importantly, (3) how their own requirements - derived by them from the O(N) external constraints - affect the selectability of the system options.

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of the NASA Pre-Phase A project life cycle phase is, "To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope." [1].

Success in achieving this purpose is at least partly defined by the efficiency with which it is achieved. Efficiency can be defined as the ratio of useful work output to total work input. In trade space exploration, useful work output can be defined as the number of selectable configurations of the system produced, N_S, multiplied by the work (time and effort) required to produce and evaluate the selectable configurations, W_S. The total work input can be defined as the sum of the useful work and the non-useful work - the number of non-selectable configurations of the system produced, N_{NS}, multiplied by the work (time and effort) required to produce and evaluate the non-selectable configurations, W_{NS} - as depicted in Equation 1 below .

$$Efficiency = \frac{N_S \times W_S}{N_S \times W_S + N_{NS} \times W_{NS}} \quad (1)$$

Too often, Pre-Phase A efforts result in a narrow spectrum of concepts, and/or in concepts that cannot be selected for reasons such as cost, cost risk, and/or technical risk. Doing more work (working harder) is not the answer, because without a change in fundamental approach, overall efficiency goes unchanged. Working smarter is the answer.

Selectability comes from the union of customer desirability, technical feasibility, and economic viability, an idea that originated from IDEO in the early 2000s [2] as depicted in the Figure 1 that follows.

978-1-7821-2734-7/20/$31.00 ©2020 IEEE

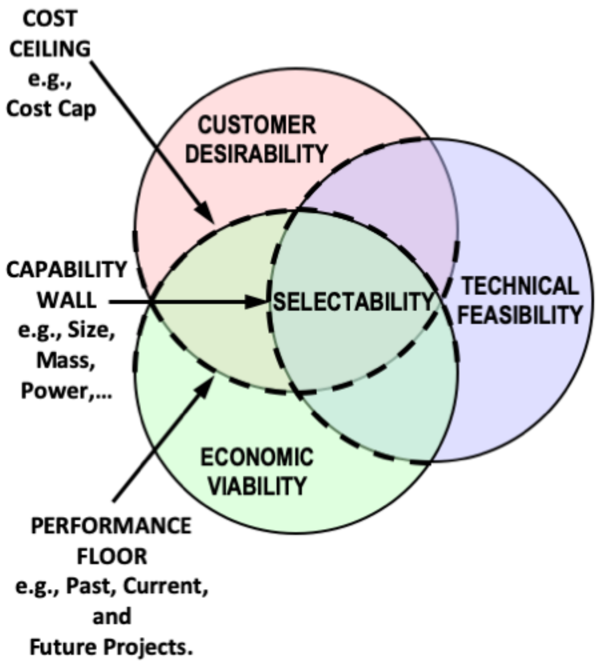


Figure 1. Selectability exists in the union of Customer Desirability, Technical Feasibility, and last, but not least, and arguably foremost, Economic Viability (after IDEO)

It is important to note that the Customer in this schema is not the proposer of the system (often the customer of the concurrent design team), but rather the end purchaser/user of the system (e.g., NASA).

In this schema, there is a "performance floor" in the customer's desirability, set by the existing solution to the customer's needs. There is also, implicitly, if not explicitly, a "cost ceiling" for the economic viability of the system. In some situations, there is also a "technical wall" set by technical resource limits (such as the canonical Size, Weight, and Power (SWaP)) arising from an external system interface, but in all cases, there is the technical internal self-consistency required to have a solution be inside the set of "technically feasible" options.

2. Paper Organization

In this paper we describe a process that has been demonstrated to cut the time it takes Team-X at the Jet Propulsion Laboratory to produce a broad spectrum of ideas and alternatives for missions, from which new programs/projects can be selected, from a nine hours per option to one hour per option – a factor of nine improvement in efficiency.

In the sections that follow we describe the principal processes and tools that enable the production and evaluation of a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected.

Reduction in Detail

Computational efficiencies are gained, and broader trade spaces are explored, without sacrificing accuracy, by reducing the detail in the options explored.

Pre-Filtering Non-Selectable Options

Computational efficiency is improved in both increasing the number of selectable options and decreasing the work on non-selectable options, by filtering option elements against the external, O(N) figures of merit first, and then only proceeding to filtering against internal, O(N^2-N) figures of merit if warranted.

Cognition Enhancing Dashboard

An N-squared diagram-based dashboard increases stakeholder cognitive efficiency by helping them gain insight into: (1) how the external boundary conditions inform the what productive internal subsystem choices are, (2) how the internal subsystem choices affect the selectability of the options, and perhaps most importantly, (3) how their own requirements - derived by them from the O(N) external constraints - affect the selectability of the system options.

3. Reduction in Detail

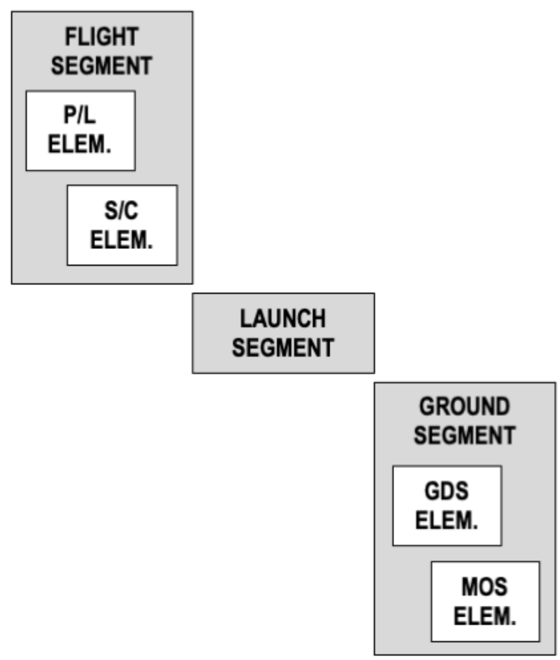


Figure 2. An N-Squared Diagram [3] for the efficient, broad, trade space exploration of space systems

In order to produce and evaluate the broadest possible spectrum of options, different paths in decisions at the lowest level of detail in the system need to be considered, in much the same way that the broad canopy of a tree results from the differences in the growth directions of the main branches, and not in the differences in the growth directions of the individual leaves. Arguably, the lowest level of detail in a space system is the Segment Level consisting of Flight

Segment, Launch Segment, and Ground Segment. The next level of detail within the Flight Segment, the element level consisting of the payload (sensor) element(s), and the spacecraft elements (e.g., Cruise, Entry Descent and Lander (EDL), and Lander elements of a mission to Mars) are an essential level of detail in a trade space exploration for a science space mission. The level of detail that has led to a factor of nine improvement in the efficiency of the broad trade space exploration of space systems in Team-X at the Jet Propulsion Laboratory is depicted in the preceding Figure 2.

However, the typical Concurrent Design Facility, like Team-X, determines the technical and cost feasibility of a mission concept using subsystem level, quasi-grassroots tools, requiring a dozen or more individuals days to weeks to produce and evaluate each option. This is more time and other resources than is typically available to a project in Pre-Phase A.

There are, however, other production and evaluation techniques than bottoms up, grassroots methods. Amongst these are analogy and parametric based techniques [4].

Through its access to information about actual space missions, and its vast array of space mission studies, now numbering in the thousands, Team-X can pull the analogy-based performance, technical, and cost information necessary to produce and evaluate options at this lower level of detail. The structure of the entries in a database necessary for segment/element level trade space exploration is depicted in Tables 1(a), (b), (c), and (d) below.

Table 1(a). Typical Payload Analogy Database Entries

Payload Element Analogy Name	
Unit Cost ($M)	
TECHNICAL RESOURCE SUMMARY	
	ACCOMMODATION REQUIREMENTS
	HXWXL Dimensions (m)
	Mass (kg)
	(Peak) Power (W)
	(Average) Power (W)
	Data Rate (Mbps)
PERFORMANCE SUMMARY	
Radiometric	Range (J)
	Resolution (J)
Spatial	Range (FOV deg.)
	Resolution (iFOV deg.)
Spectral	Range (nm)
	Resolution (nm)
Temporal	Range (exposure sec)
	Resolution (rate sec)
Polarimetric	Range (deg.)
	Resolution (deg.)

Table 1(b). Typical Spacecraft Analogy Database Entries

Spacecraft Element Analogy Name	
Unit Cost ($M)	
TECHNICAL RESOURCE SUMMARY	
ACCOMMODATION CAPABILITIES	**ACCOMMODATION REQUIREMENTS**
HxWxL Dimensions (m)	HxWxL Dimensions (m)
P/L Mass (kg)	Mass (kg)
P/L (Peak) Power (W)	
P/L (Average) Power (W)	
P/L Data Rate (Mbps)	
P/L Data Storage (GB)	
PERFORMANCE SUMMARY	
ACS Pointing	Knowledge (deg)
	Control (deg)
	Stability (deg)
Propulsion	Delta V (m/s)
Telecomm	Uplink Band
	Uplink Rate (kbps)
	Downlink Band
	Downlink Rate (Mbps)

Table 1(c). Typical Launch Service Analogy Database Entries

Launch Service Segment Analogy Name	
Unit Cost ($M)	
TECHNICAL RESOURCE SUMMARY	
ACCOMMODATION CAPABILITIES	**ACCOMMODATION REQUIREMENTS**
HxWxL Dimensions (m)	Launch Location(s)
PERFORMANCE SUMMARY	
ORBIT TYPE	PERFORMANCE
LEO Polar	Mass to Altitude Curve
LEO Inclined	Mass to Altitude Curve
GTO	Mass to Altitude Curve

Table 1(d). Typical Ground Segment Analogy Database Entries

Ground Segment Analogy Name	
Development Cost ($M)	
Cost per Data Pass ($M)	
TECHNICAL RESOURCE SUMMARY	
Station Locations	
Data Volume (TB)	
Data Product Levels (0, 1, 2, 3,…)	
PERFORMANCE SUMMARY	
Telecomm	Uplink Band
	Uplink Rate (kbps)
	Downlink Band
	Downlink Rate (Mbps)

In situations where the available analogies are too sparse as a function of parameter space, parametric methods, such as linear interpolation or Taylor Series expansions, have been constructed from the larger database.

4. PRE-FILTERING NON-SELECTABLE OPTIONS

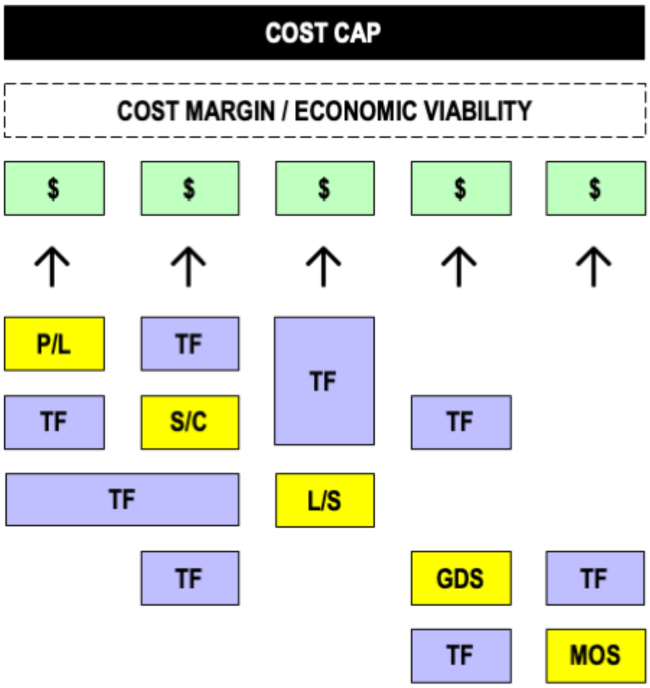


Figure 3. Filtering the options for consideration in the (yellow) element analogy choices for payload (P/L), spacecraft (S/C), launch service (L/S), ground data system (GDS), and mission operations system (MOS) based on cost (green) *before* working through all the (blue) inter-element technical feasibility interfaces (TF) (based on technical resource (e.g., SWaP) requirements and capabilities) as depicted in the N-squared diagram above, is more computationally efficient than the other way around

In most Concurrent Design Facilities, although the technical design work on individual options is concurrent, the overall process is often still serial. Most trade space explorations start with the performance desired on behalf of the customer (e.g., coverage, data latency, etc.), which then proceeds to the finding of a technical solution, and finishes with a cost estimate. As discussed above, one of the principal attributes of selectability is economic viability. Unfortunately, most options produced and evaluated in this serial manner end up with costs in excess of the cost ceiling – reducing overall efficiency through non-useful work.

The work of evaluating the technical feasibility of an option scales with the number of off-diagonal elements in an N-squared diagram, or O(N^2-N). The financial viability of an option, however, only scales with the number of on-diagonal elements in an N-squared diagram, or O(N).

Since N < N^2-N for N > 2, Team-X filters the options for technical evaluation down to only those elements are financially viable, a process enabled by the analogy and parametric tools described above and the fact that total project cost for a configuration can be estimated from the sum of the element costs plus wraps [5]. This increases the efficiency of the trade space exploration as work is not put into fully technically fleshing out economically non-viable options.

In some cases, there are externally imposed technical resource limits on the system (e.g., volume or mass capabilities of predicated launch vehicles, or from another interfacing system – such as the International Space Station). In these cases, the element combinations under consideration for the trade space exploration can be pre-filtered on the O(N) totals of those technical resources (such as mass, power, etc.) before the internal O(N^2-N) technical self-consistency is evaluated. This once again increases the efficiency of the trade space exploration as work is not put into fully fleshing out options that are technically in-feasible due to external constraints on the system.

5. COGNITION ENHANCING DASHBOARD

Stakeholders often demand to have a role in the production, evaluation, and selection of options to put forward during trade space exploration.

However, stakeholders often lack insight into the ramifications of the technical elements they desire (demand) to see included in all options produced and evaluated. Stakeholders also often lack insight into the ramifications of the derived performance requirements they impose on the system, and the subsequent effect these derived requirements have on the selectability of the system, particularly with respect to cost.

The result is a decrease in the efficiency of the trade space exploration as increasing amounts of work are desired (demanded) by the stakeholders to be put into making non-selectable options selectable. Efficiency can be regained only by helping the stakeholders transition more quickly through the stages necessary to accept [6] the results of the trade space exploration.

This lack of insight stems from an inability to simultaneously (and literally) see the performance, technical and cost aspects of a system option as it is being produced and evaluated, because these aspects are often bookkept within separate ledgers, and displayed on different screens within a concurrent design facility.

In order to deal with this ultimate factor in the overall efficiency of trade space exploration, an N-squared diagram-based dashboard was developed to keep the performance desirability, technical feasibility, and economic viability aspects of all the elements of the system all in view of the stakeholders, on one screen, simultaneously.

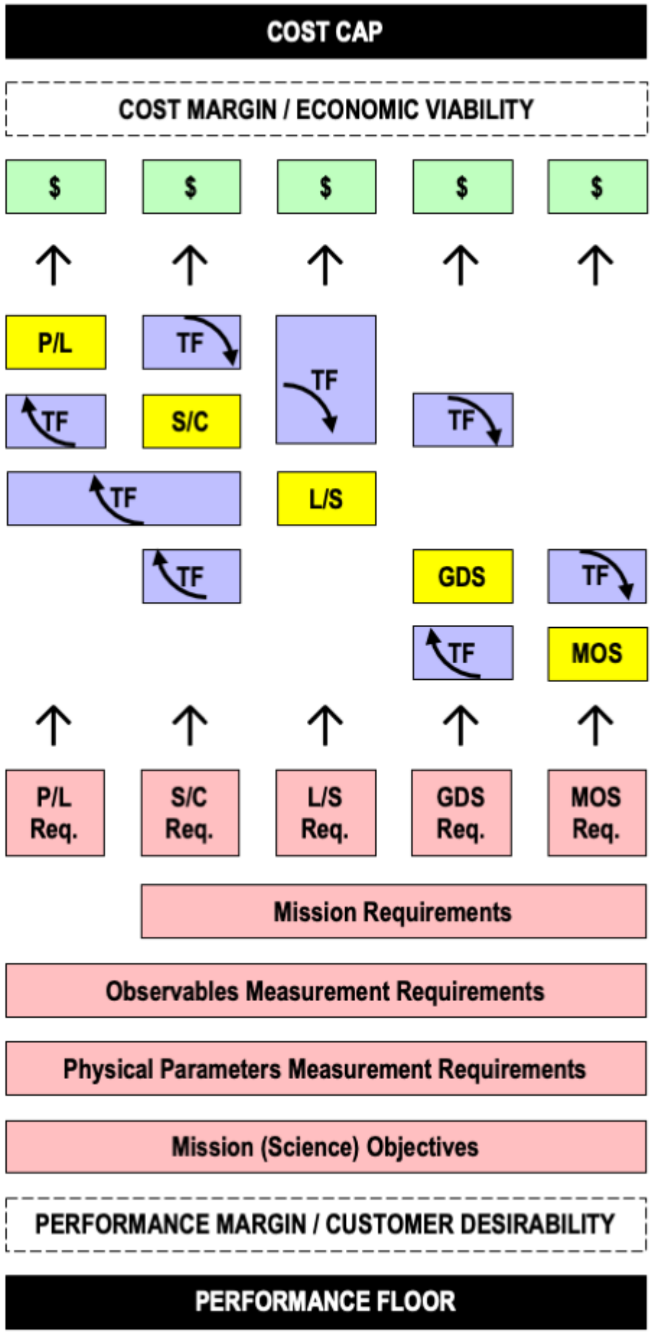


Figure 4. An N-Squared Diagram based Concurrent Figures of Merit Dashboard improves stakeholder insight into, and cognition of, the ramifications of their choices by aligning performance requirements, technical resource requirements, and cost requirements with the elements in the trade space.

With this dashboard layout, stakeholders gain insight into the cost and technical ramifications of the elements they desire (demand) to see included in the options produced and evaluated in the columns and rows of the dashboard. The stakeholders also gain insight into the ramifications of the derived performance requirements they (unknowingly) impose on the system, and the subsequent effects on the selectability of the system, particularly in cost, along a straight vertical column from requirement to cost.

6. CONCLUSIONS

The principal processes and tools that enable the production and evaluation of a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected – i.e., analogy based tools for detail reduction, pre-filtering of options for selectability, and a concurrent figures of merit dashboard to enhance stakeholder cognition - have led to a factor of nine improvement in the efficiency of trade space exploration of space systems in Team-X at the Jet Propulsion Laboratory.

While these processes and tools lack the precision of a typical subsystem level concurrent design facility study, they have enabled dozens of explorations of broad trade spaces within the limited time and other resources typically available to projects in Pre-Phase A.

These processes and tools have to date only been applied to Astrophysics, Earth Science, and Planetary Science mission concepts, but the general approach should be applicable to a broad range of Space Missions.

ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] NASA Systems Engineering Handbook, NASA SP-2016-6105 Rev2, 2016, p. 9

[2] T. Brown, *Change by Design, Revised and Updated: How Design Thinking Transforms Organizations and Inspires Innovation*, New York, New York: Harper Business, 2019.

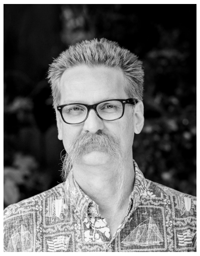
[3] R. Lano, *The N2 Chart*, Redondo Beach, CA: TRW Software Series, 1977.

[4] H. Kerzner, “Pricing and Estimating,” in *Project Management: A Systems Approach to Planning, Scheduling, and Controlling 12th Edition*, Hoboken, New Jersey: Wiley, 2017.

[5] J. R. Wertz and W. J. Larson, “Cost Modeling”, in *Space Mission Analysis and Design (SMAD) - 3rd Ed.*, Torrance, CA: Microcosm, 1999.

[6] E. Kübler-Ross and D. Kessler, *On Grief and Grieving: Finding the Meaning of Grief Through the Five Stages of Loss*, New York, New York: Simon & Schuster, Inc., 2005.

BIOGRAPHY



Alfred Nash *is currently the Lead Engineer of Team-X at the Jet Propulsion Laboratory. Alfred has a Ph.D. in Physics from the University of California, Santa Barbara, and a B.S. in Physics from Stanford University. Alfred has been with JPL for more than 25 years. Before the past 12 years spent dedicated to mission formulation, Alfred worked in the implementation of a variety of space flight missions including: SIRTF/Spitzer, Planck, and the Orbiting Carbon Observatory.*